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Home Energy Management System using a 4G Cellular Communication

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Abstract- The growth of home energy consumption due to the increasing demand has become a crucial issue in the worldwide energy sector. The conventional nature of electrical grid makes these challenges exacerbate. Thus, the current situation should be improved by adopting an efficient energy management system as a solution to reduce electricity cost, efficiently use energy and avoid the waste of resources. This paper addresses a home energy management system that enables a remote management of electrical consumption by means of optimization. Furthermore, it sheds light on establishing a secure communication between the user interface application and the module located in the house using 4G cellular networks. Finally, a draft cost study of the suggested system is presented.

Keywords**:** *Home Energy Management System; Security; 4G.*

I. INTRODUCTION

The changing face of energy consumption due to the proliferation of user devices and appliances requires a very specific approach to achieve the ultimate goals of optimizing energy usage, reducing cost and shaving peak demand while maintaining high quality operating levels [1]. To accomplish the aforementioned goals, the use of a real time functioning system is indispensable. This approach uses collaborating elements in order to get the precise information to be processed and used for taking the appropriate decisions [2]. Introducing management at the demand side enables the achievement of energy optimization along with cost reduction. The latter is achieved by allowing the user to be aware of his consumption; as a result, the necessary decisions are made at the customer level in order to reduce the cost as well as the energy use.

However, giving the user the power to control his appliances definitely has drawbacks such as system intrusions. This comes as a result of using unsecured network to establish the two-way flow of data which is crucial for the functioning of the Home Energy Management system. The emerging systems use the conventional wireless network Wi-Fi (IEEE 802.11) which is more vulnerable to Hijacking if the Wi-Fi is unencrypted. Thus, this paper sheds light on the security intrusions that may arise at the communication level and propose an alternative network to establish a safe data flow. The proposed network, 4G, is more secure in the sense that it enables the encryption and decryption of data. Since the consumer has limited knowledge to make security related decisions, the suggested system proposes an adapted design enabling the user to securely manage his appliances without worrying about security measures.

This paper is structured as follows: Section II presents the related work, while Section III details the system architecture and the corresponding system design is discussed in Section IV. Section V presents a draft of cost study and finally, Section VI draws the conclusion of the paper with future work.

II. RELATED WORK

There are different existing home energy management systems that succeed in realizing some of the essential requirements of such systems; however, they fail to fulfill other requirements. This set of requirements evaluates the home energy management systems based on different criteria such as monitoring, disaggregation, availability, affordability and accessibility [3], [4]. One home energy management system that somehow succeeded in implementing these requirements is based on the Pervasive Service-Oriented Networks (PERSON) framework which is composed of three layers: The first one is a heterogeneous network stage that supports information exchange to the upper layers through the application programming interfaces (APIs). The second one is a service- oriented network that provides modularity and interoperability. The final layer is a context aware intelligent algorithm, which includes intelligence for active control and system optimization. The PERSON system provides many useful features and services, which include monitoring, control, low cost and low energy consumption. Nevertheless, it lacks providing privacy and security [5]. An alternative to this system is the open source service-oriented framework called WattDepot for energy management which comprises three parts in its process: sensors which are software processes that request the data from energy meters, services and clients who can request the data through the servers. Nonetheless, WattDepot also has some major constraints such as the deficiency in intelligence and the need for a programmable or automatic control [6]. A proposed home energy management system in 2009 uses the Zigbee module which is an intelligent wireless communication platform. This system provides several functionalities such as energy monitoring, energy control, protection control, carbon emission suppression, safety and overheats protection. It also offers an easy to understand graphical user interface based on Visual Basic software. Even so, this system has some limitations which are the lack of privacy and the absence of a desktop application implementation [7].

This papers' main concept is to propose a protected network to enhance security measurement in order to allow the user to properly and safely use the Home Energy Management (HEM) system.

III. HOME ENERGY MANAGEMENT SYSYTEM ARCHITECTURE

In this paper, the HEM system architecture is proposed to solve the main issue tackled which is the optimization of energy by focusing on establishing a secure communication line. The system architecture is established in order to demonstrate the connections between the different levels of the system ranging from the interface layer to the physical layer. This section illustrates the correlation between the layers followed by a description of each layer.

Figure 1 shows the different elements of each layer and the flow of data between the layers. The first data flow direction is from the user to the Smart plugs. As soon as the user sends the command, switching On/Off an appliance, data is sent to the gateway using 4G network then to the smart plugs using Zigbee protocol. After processing the data, the instructions are sent to the actuators in order to be applied at the appliances level. This sequence of steps is applicable inversely starting from the sensors that sense the appropriate quantities and sends the data to the smart plug using Zigbee protocol. Then, this data is sent to the user device from the gateway using 4G network.

A. Physical layer

The physical layer is composed of four main components. The first element is the home appliances which are simultaneously related to the sensors and actuators. They represent the second element of the layer where: the sensors sense the different quantities such as current and temperature which are then reported to the control unit. As for the actuators, the relays receive the commands sent by the control unit and then execute them. The third element is the control unit, the one used is an Arduino microcontroller, whose main role is to process the information received by the sensors and sends the commands to the actuators. The final element is The Skywire™ Arduino Cellular Shield which is a 4G module that is used to establish a communication between the Zigbee module that represents the communication layer and the user device. The choice of these components is discussed in the HEM system design.

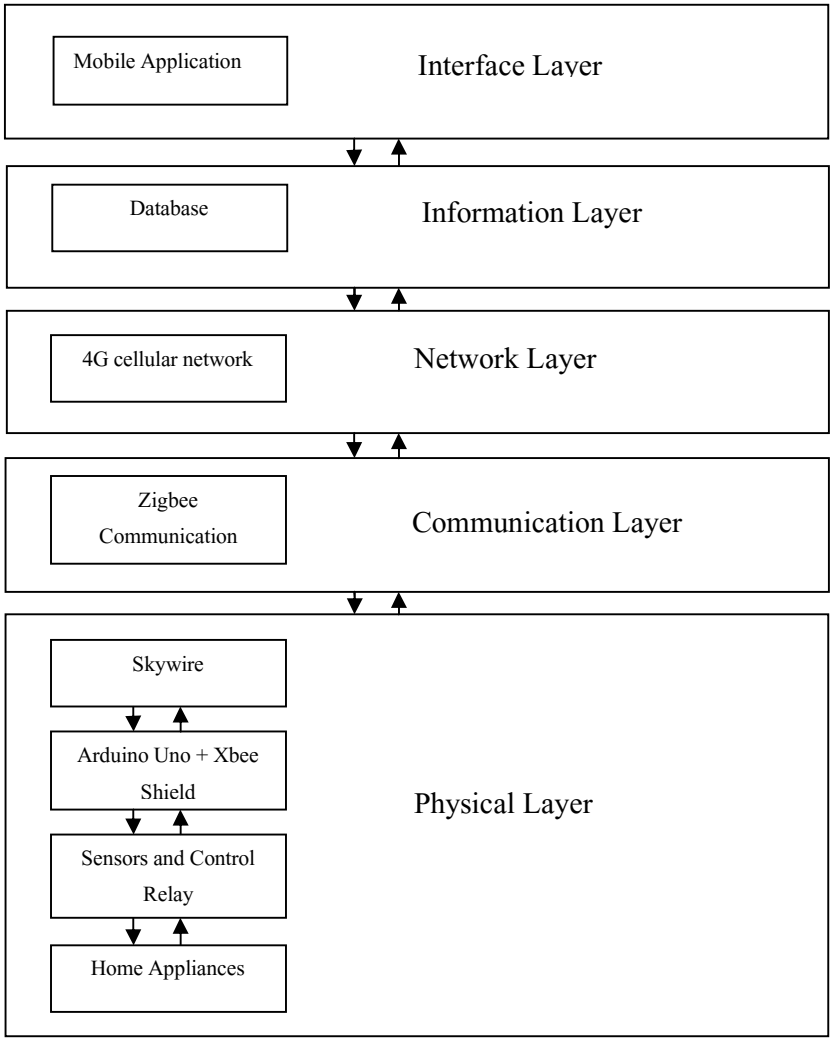

Figure 1. *System Architecture*

B. Communication Layer

The Zigbee Module is responsible for establishing communication between the physical layer and the network layer by normalizing a general set of communication protocols between the devices. The choice of the Zigbee module is further detailed in the next section.

C. Network Layer

The network layer is the main link between the lower level data which is the communication layer and the higher level system which is the information layer. Its major role is to transfer data about the energy consumption from the gateway to the user device, more specifically to the database and send commands from the user device to the gateway. In order to do that, 4G cellular networks is used to safely and rapidly send and receive data.

D. Information Layer

The information layer is composed of the database or data warehouse. The database allows storing the collected data about the electricity consumption sensed by the smart plugs of the different home appliances. These data can then be used by the user to monitor and optimize his electricity consumption. The system should have a continuous access to the electricity consumption of the different devices in the home using the network layer and should display the data in the interface layer.

E. Interface Layer

The mobile application is the end-user interface which displays for the user the energy consumption of each home appliance and allows him to manage them by turning the devices on/off. The mobile application shall use a friendly, simple and clear graphical user interface which can be used by any customer.

IV. HOME ENERGY MANAGEMENT SYSTEM DESIGN

A. System Specification and Requirements

As mentioned, the HEM system should achieve specific requirements to have a complete functional system. First, the suggested system should enable the user to track the energy consumption of every single appliance, monitor these appliances by switching them on/off remotely and control them automatically in case of overloading. Then, it is necessary to have a disaggregated system able to provide real time data exchange in order to keep track of the energy consumption. Moreover, it should integrate other information generated from the sensors such as temperature and motion in order to be able to have access to historical data which can be used to make the appropriate decisions regarding energy optimization. The system should also be available to the user via a user friendly interface which is accessible, simple and affordable. Another important requirement of the HEM system is security and privacy; the system should be securing both the communication line and the user's consumption profile. Finally, the system should perform intelligent actions using specific algorithms to facilitate the user's tasks as he may not have enough knowledge to make the necessary decisions [8].

B. Wi-Fi vs. 4G Network

a. Wi-Fi and Security

Wi-Fi is a wireless communication technology with limited range that enables devices to access internet and exchange data. As it is widely used, the exposure to hijacking is high especially if the access point is public. Indeed, hackers use Evil Twin technique to lure out peoples information. This technique consists of using a similar name with the Wi-Fi access point which makes it hard for the user to differentiate between the real and compromised network.

Furthermore, Wi-Fi is exposed to many intrusions since the public access points (AP) do not use passwords or hide their ID which makes it easier for the attacker to hijack the information. Thus, in this system, a secure wireless communication is established to protect user privacy [9]. Figure 2 demonstrates both the path taken by a client when directly connected to the server and the path taken when an attacker is accessing all the data sent and received by the client.

It is usually hard for a user to distinguish between the connection speed of a normal case, where the client interact directly with the server and the case where an attacker is hijacking data sent and received by the client. However, using a trace route command, it is actually possible to measure the difference in time delay between each case. Table 1 illustrates the results obtained for the two cases from the trace route command [9].

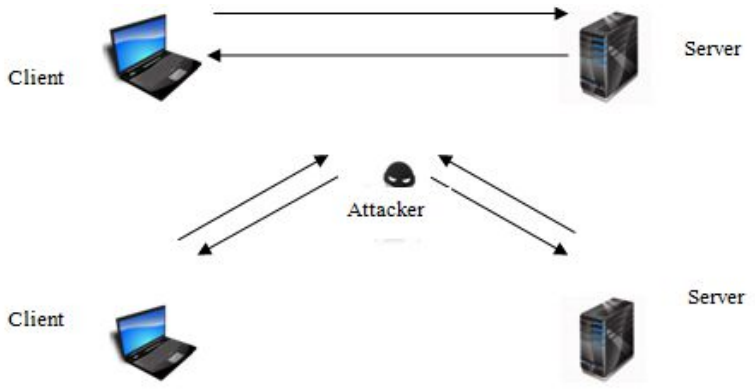

Figure 2. *Direct Connection and Connection through an Attacker*

Table 1. *Time delay comparison between direct connection and connection through an attacker*

	Component	Average Time
Direct Connection	Client	1.831
	Server	5.574
Connection through Attacker	Client	10.834
	Attacker	7.639
	Server	6.164

As demonstrated in Table 1, when the connection is going through an attacker a time delay is added to the communication time, though it is not detectable directly by the user. Hence, the use of Wi-Fi is not a reliable in this system where the confidentiality of the user is of a high importance. For this reason, the chosen network for the HEM system is 4G which is a more secure and reliable network.

b. 4G network

4G is a more secure network for data transmission since the data are encrypted using AES algorithm, a symmetric block cipher that encrypt /decrypt information, resulting in a secure connection between the two ends of the communication line [10]. The aim of AES algorithms is to guarantee the security and confidentiality of the user and to ensure a fast data acquisition and transmission by adopting the EPS Encryption Algorithm (EEA). The latter is based on bitwise operations that are executed promptly [11]. Figure 3 provides a detailed description of the EEA structure.

Figure 3 shows the hierarchy of the EEA structure where first a cipher key (a type of multiple alphabetic substitutions) is needed to form the key stream which is a stream of arbitrary or pseudorandom characters. The latter is combined with the plain text using the AES algorithm, after processing the data a cipher text is then acquired as an output. To further explain the EEA, figure 4 illustrates the encryption/decryption process.

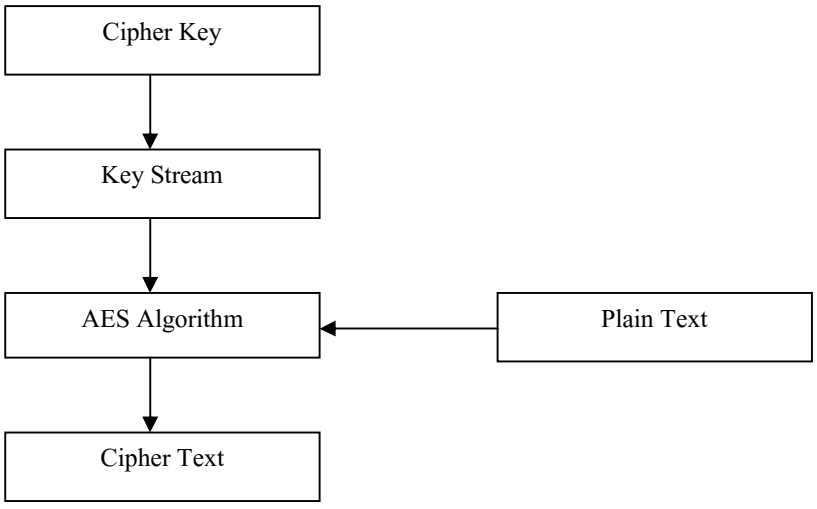

Figure 3. *EPS Encryption Algorithm Structure*

Figure 4. *Encryption/Decryption of Data using EEA*

To encrypt the data a plain text is sent to the EEA that cipher the information resulting in a cipher text. Inversely, in order to decrypt, the cipher text is sent to the EEA using the same logic to convert it to the plain text.

Accordingly, due to the aforementioned security enhanced algorithm, a 4G module is used in the HEM system to establish the communication between the user device and the gateway of the house. To initiate this communication, an implementation of the Skywire™ Arduino Cellular Shield is necessary. The Skywire module is compatible with Arduino (The microcontroller used to control the HEM system) and allows an easy connectivity to 4G cellular network.

C. Home Energy Management System Components

In the next section a detailed analysis of the system components and the choice of the materials as well as their specifications are presented. The main components that are going to be discussed are: microcontroller, wireless communication modules, sensor and actuators.

a. Microcontroller

The control unit is required to get the input data from the user, process them and then send them to the actuators or to get the information from the sensors and send them to the user. Thus, a digital control unit is needed to be the bridge between the above mentioned components. In the context of this system, an Arduino microcontroller is used.

Indeed, Arduino Uno which is an open source platform board based on the ATmega328P constitutes two layers of the system architecture (The smart plug and the gateway) [12]. Arduino Uno provides several functionalities such as:

- Storing Data which are collected by sensors
- Sending data via the Zigbee module to the gateway wirelessly
- Updating the data in the database via 4G
- Receiving the user commands and sending them to the smart plugs

The specifications of Arduino Uno presented in Table 2 prove that it is an energy efficient microcontroller suitable for the HEM system since it does not require high energy to function. In addition, multiple platform options are provided such as Windows and Linux to solve compatibility issues between the user device and the platform used.

Table 2. *Arduino Uno Specifications*

Part	Specification
Operating Voltage	5V
Input Voltage (limit)	6-20V
Digital I/O Pins	14
Analog Input Pins	6
DC Current per I/O Pin	40 mA
DC Current per 3.3V Pin	50 mA
Flash Memory	32KB

b. Wireless communication

i. Zigbee module

To guarantee the communication of the sensors and actuators with the control unit, a communication protocol is needed. When comparing the existing one such as infrared, RF module, Bluetooth and Zigbee, it has been proven that the Zigbee module is more convenient to be used in home network due to its low power consumption and high coverage range [13]. In this system, ZigBee wireless module is used to transmit and receive data between the Arduino and the home server. The aforementioned comparison is presented in Table 3.

Table 3. *Transmission Media Comparison*

Item	**Type**			
Characteristics	Infrared	RF Module	Bluetooth	Zigbee
Power Consumption	Low	Medium	Medium	Low
Controlled units	1	1	7	254
Distance	15 m	50 m	100 m	100 m
Transfer Rate (Kbps)	38	4800	1000	250

ii. Xbee shield

The Xbee shield allows a wireless communication between Arduino board and Zigbee. The module communicate up to 100 feet indoors or 300 feet outdoors and it can be used as a serial/usb replacement or put it into a command mode [14].

c. Sensors

A variety of sensors is used in this system depending on the different quantities needed to be measured. A detailed description is provided in the section below.

iii. Temperature Sensor

In order to prevent overheating, a temperature sensor is needed. The temperature and humidity sensor used for this system is SEN11301P which provides a pre-calibrated digital output. This sensor detects and measures temperature and humidity due to its unique capacitive element. It also has an excellent reliability, long term stability, provides full range temperature compensation (calibrated) and a low power consumer [15]. Table 4 represents the main specifications of the temperature sensor.

Table 4. *Temperature & Humidity sensor SNE11301P Specifications*

Part	**Specification**
Work Voltage	3.3V – 5V
Measuring Range Humidity	20%-90% RH
Measuring Range Temperature	0-50 °C
Accuracy Humidity	±5% RH
Accuracy Temperature	±2°C
Sensitivity Temperature	1°C
Sensitivity Humidity	±1% RH
Signal Collecting Period	2S

i. Light Sensor

A light sensor is necessary to measure the amount of light in the house; therefore, it does serve to reduce the energy consumption by detecting the existence of motion. Thus, in this paper, the module used in this project is the SEN10171P which is based on the I2C light-to-digital converter TSL2561 to transform light intensity to a digital signal. It differs from the traditional analog light sensor because it is a digital module that features a selectable light spectrum range due to its dual light sensitive diodes: infrared and full spectrum [16]. The main specifications of the sensor are presented in Table 5.

Table 5. *Light Sensor Specifications*

Items	Min	Max
Operating Temperature	-30	70
SCL,SDA input low voltage	-0.5	0.8
SCL,SDA input high voltage	2.3	5.1

ii. Current transformer sensor

In order to avoid overloading, current transformer sensor is used. The one proposed in this system is SCT-013 which is used to measure alternating currents [17]. Table 6 represents the main characteristics of the current transformer sensor.

Table 6. *Current Transformer Sensor Specifications*

Parts	Specification
Input Current	0-100 A AC
Output	Mode 0~50mA
Non Linearity	±3%
Work Temperature	25°C ~ + 70°C

d. Actuators

To apply the necessary commands sent, the use of actuators is indispensable. The ones used in this system are relays. The Relay Shield provides a solution for controlling high current devices that cannot be controlled by the Arduino's Digital I/O pins due to their current and voltage limits. The Relay Shield has high quality features. It is equipped with LED indicators to show the on/off state of every relay related to each home appliance and a standardized shield to provide an easy connection to the Arduino board [18]. Table 7 represents the Relay Shield specification.

Table 7. *Arduino Uno Specifications*

Item	Specification
Supply Voltage	5.25
Working Current	250
Switching Voltage	35
Switching Current	8

D. System Workflow

The HEM system is based on a user friendly interface where the user can select a specific command from the commands list. Figure 5 illustrates the workflow of the HEM system, where the command is sent to the gateway of the HEM system via the 4G network. Subsequently, the command is sent to the microcontroller in order to be processed then transferred to the actuators which does the action of turn either On/Off the appliance based on the command type. Inversely, the alternative workflow starts at the sensors level which sense various aspects of the home appliances. The signals reported by the sensors are sent to the control unit which processes them and send the necessary data to the gateway via the Zigbee protocol. The data are finally sent to the user device via 4G network.

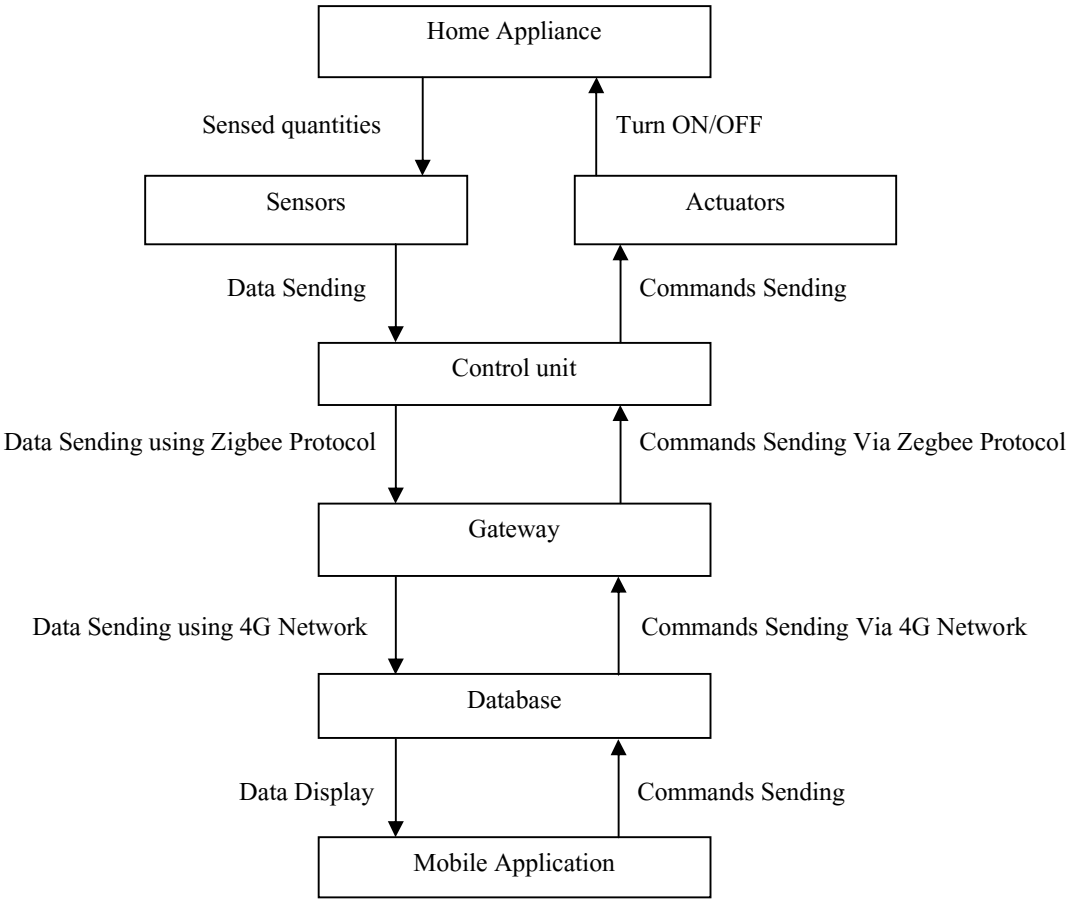

Figure 3: *System Workflow*

V. SOCIAL AND ECONOMICAL ANALYSIS

It is important in designing any system to check if it meets some social and economical factors in order to have an efficient and ethical system. This section presents these social and economical factors that affect the home energy management (HEM) system.

- Societal: Society faces the continuously increasing demand in the energy sector. Home energy management systems are a way to manage the electricity consumption and adapt to the changing behavior of the society.
- Technological: Electrical energy can be tracked and managed via a home energy management system thanks to the creation of powerful microcontrollers and of the wireless communication platforms.
- Environmental: Fossil fuels, which are extremely harmful for the planet, are the main sources of electricity. In order to limit the greenhouse effect and the emissions of pollutants, an efficient use of energy is crucial.
- Ethical: The most important feature of the HEM System is to provide a secure and private application for users to track and manage the appliances in the house.
- Political: The HEM System is a useful way for the government to ensure the energetic interdependence of the country to oil producing countries.
- Economical: The main goal of the HEM System is to track and manage the appliances in the house, it will have several long term benefits because the user will be able to track the energy consumption of each appliance and save money by lowering the electricity bills:

In this section, we estimate the total cost of two different home energy management systems. The first one is the HEM system presented in this paper which is based on the implementation of the Skywire Arduino Cellular Shield, while the other one is based on the Arduino Ethernet Shield. Tables 8 and 9 summarize the corresponding cost study of both systems [19], [20], [21].

Table 8. *Cost Study of the HEM system based on Skywire Shield*

Device	Cost (MAD)
Arduino Uno	362.21
Arduino Xbee Shield	912.6
Light Sensors	53.82
Temperature Sensors	53.82
Current Transformer Sensor	88.20
Skywire™ Arduino Cellular Shield	402.19
Relay Control	71.10
TOTAL	**1943.94**

Table 9. *Cost Study of the system based on Ethernet Shield*

Device	**Cost (MAD)**
Arduino Uno	362.21
Arduino Xbee Shield (2)	1825.2
Light Sensors	53.82
Temperature Sensors	53.82
Current Transformer Sensor	88.20
Shield Arduino Ethernet	452.4
Relay Control	71.10
TOTAL	**2906.75**

From Tables 8 and 9, it can be concluded that the cost of the HEM system proposed in this paper is lower compared to the other home energy management system. All components of both systems are the same except for the shield responsible for establishing the internet connection. The direct implementation of the Skywire Arduino Shield instead of using the Ethernet Arduino Shield which requires an extra Xbee shield to establish the connection with the Arduino Uno makes the difference in the total price between the two systems approximately 1050 MAD. Figure 6 illustrates a graphical comparison pertaining to the estimated cost of the two systems. It is noticeable that adding one more Arduino Xbee Shield in order to establish the communication between the gateway and the user device when dealing with Ethernet network increase the total cost of the system. While, for the HEM system it is easier to connect the gateway to the internet via using the Skywire Shield that does not require an intermediate to connect to the Arduino Uno.

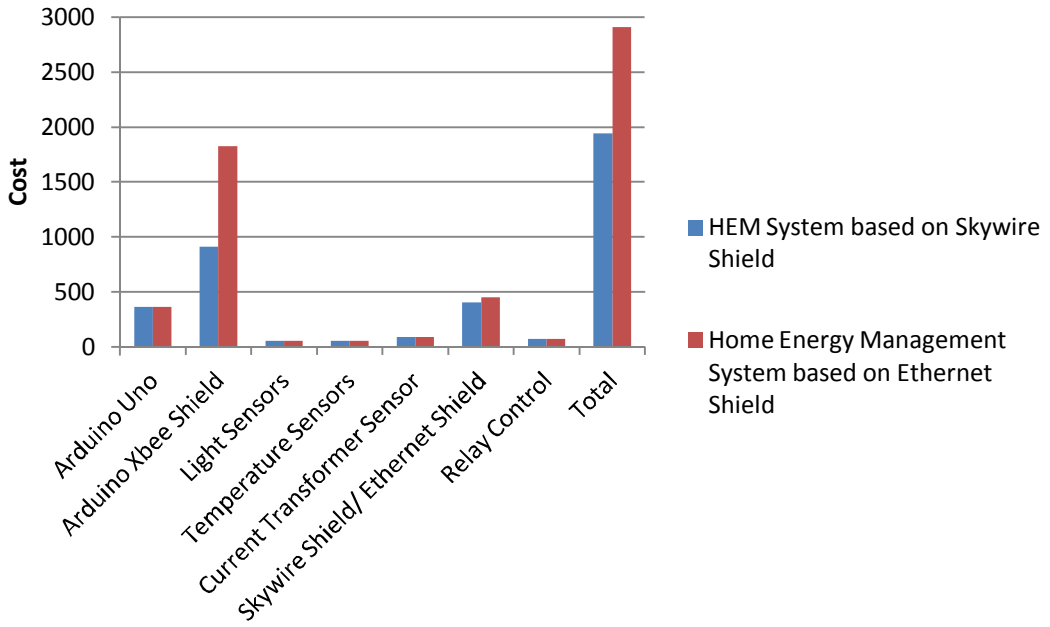

Figure 6. *Graph Comparing the Cost of the two considered systems*

VI. CONCLUSION

This paper proposed a Home Energy Management system that emphasizes the use of a secure network in order to achieve the ultimate goal of optimizing energy while keeping a high level quality of operating levels. The HEM system consists of establishing a two way flow of data, where the commands are sent from the user to the gateway through a 4G network and from the gateway to the smart plugs through the Zigbee module. The other workflow of data starts at the sensors level which sends the information to the Arduino Uno in order to be processed, the latter sends the data to the user device through 4G network.

To have an enhanced performance and to incorporate other features that may improve the home energy management system, there are a number of ideas that can be implemented as future work. For instance, the use of renewable energies, such as solar panels, as the main source of energy in the home energy management system can optimize the energy consumed by the user by allowing him to monitor and control the amount of energy produced by the sustainable energy source. In addition, more sensors can be used in the smart plugs such as motion sensors and humidity sensors to allow the user to have a maximum data about the home appliances.

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